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**ON THE SUPPOSED ANTICORRELATION  
OF SOLAR POLAR AND  
EQUATORIAL ROTATION RATES**

by

Thomas L. Duvall, Jr.  
Leif Svalgaard

Office of Naval Research  
Contract N00014-76-C-0207

National Aeronautics and Space Administration  
Grant NGR 05-020-559

National Science Foundation  
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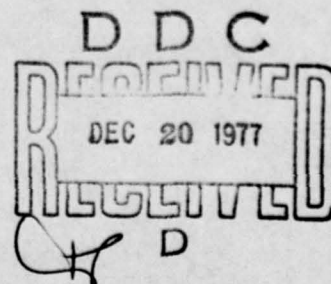
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Abstract

*(c + sin to the fourth power)*  $\rightarrow$  Howard and Harvey (1970) analyzed Mt. Wilson doppler shifts *omega* *(b x sin squared)* to obtain a daily measure of the sun's differential rotation. The data were fitted to give an angular velocity of the form  $\omega = a + b \sin^2 B + c \sin^4 B$  ( $B$  = heliographic latitude). Changes in  $a, b, c$  were found to be correlated (Howard and Harvey, 1970). (Yoshimura, 1972) used the anticorrelation of the  $b$  and  $c$  parameters to infer the existence of large-scale convection. (Wolff, 1975) used the  $b$ - $c$  anticorrelation and a weak correlation between  $a$  and  $b$  to infer that variations of the sun's polar and equatorial rotation rates are anticorrelated. In this paper, the anticorrelation of  $b$  and  $c$  is shown to be due to numerical coupling.  $\leftarrow$

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Introduction

An analysis of several years of full-disk, line of sight photospheric doppler line shifts was reported (Howard and Harvey, 1970). The data for each day's observation were fitted to a differential rotation law of the form  $\omega = a + b \sin^2 B + c \sin^4 B$  ( $B$  = heliographic latitude). The method used to get the parameters  $a, b, c$  is a full-disk, simultaneous least squares solution. So, for each day's observation independent measurements of  $a, b, c$  are derived. The parameters  $a, b, c$  were found to vary from day to day by large amounts with respect to their computed uncertainties. Variations of these three parameters were found to be correlated. Figure 1 shows the correlation of  $b$  vs  $c$  for these observations. Physical conclusions about the solar atmosphere have been drawn based upon this correlation (Yoshimura, 1972 and Wolff, 1975), the result of Wolff being that the solar polar and equatorial rotation rates are anticorrelated. In the present study, the origin of the  $b$ - $c$  correlation is investigated using a computer simulation technique. It is found that the correlation is caused by the effect of noise on the least-squares analysis used to get the parameters  $a, b, c$ .

Analysis and Conclusions

The computer simulation technique consists of the following steps:  
(1) Generating the line of sight velocity component at each point over the solar disk assuming a certain differential rotation law. The spatial resolution used was that of the observations (17 arcsec). (2) At each grid

point, gaussian random noise (of zero mean) is added to the line of sight velocity component calculated in step (1). (3) This simulated full-disk velocity scan is analyzed in the same way as the real observations were (Howard and Harvey, 1970). That is, a full-disk, simultaneous least squares analysis is performed to extract the differential rotation parameters a,b,c. (4) Steps (1)-(3) are repeated many times, each time with different values of the noise.

The amplitude of the gaussian random noise added to the simulated rotation data was fixed so that the uncertainties in the parameters a,b,c computed from the residuals matched the uncertainties computed for the real data. A scatter plot of b vs c for the simulated observations is shown in Figure 2. It is seen that the values of b and c are strongly correlated. The correlation is seen to be in the same sense as that for the real observation in Figure 1. This result strongly suggests that the b-c correlation is not a large-scale property of the differential rotation.

An attempt was made to qualitatively understand the b-c correlation. The function that is minimized in the least-square fit was investigated. This function has the form

$$X^2 = \sum_i^{\text{disk}} [V_i^{\text{observed}} - V_i^{\text{fit}}(b,c)]^2,$$

where  $V_i^{\text{observed}}$  is the observed line of sight velocity at point i on the visible disk.  $V_i^{\text{fit}}(b,c)$  is the line of sight velocity component at the observed point due to a sun rotating differentially with angular velocity  $\omega = a + b \sin^2 B + c \sin^4 B$ . By varying b and c in  $V_i^{\text{fit}}$ , we calculate  $X^2$  as a function of b and c. A contour plot of  $X^2$  as a function of b and c is shown in Figure 3. The point at the center of the ellipses (a minimum) indicates the value of b and c that would be extracted from the least squares solution. The fact that the contours are ellipses and not circles is very significant. When there is noise in the data the scatter of points will not be isotropic about the center point, but will be extended along the direction of the major axis of the ellipse.

The fact that the curves in Figure 3 are ellipses and not circles is presumably due to the nonorthogonality of the polynomials making up  $V_1^{\text{fit}}$ . The polynomials in  $\sin B$  making up  $\omega$  ( $1, \sin^2 B, \sin^4 B$ ) are not orthogonal. To see if this is important, computer simulations were performed in which the angular velocity  $\omega$  was constructed from orthogonal polynomials. The form of the angular velocity function was

$$\omega = a_0 P_0(\sin B) + a_2 P_2(\sin B) + a_4 P_4(\sin B),$$

where  $P_0, P_2, P_4$  are the zeroth, second, and fourth order Legendre polynomials and  $a_0, a_2$ , and  $a_4$  are variable parameters. In a computer simulation similar to that used to derive the b-c correlation, it was found that the  $a_2$  and  $a_4$  parameters were strongly correlated. So the correlation of parameters in the fit is independent of the form chosen for  $\omega$ . The correlation is probably caused by the geometrical factors (which are functions of the latitude  $B$ ) which multiply  $\omega$  in the construction of the line of sight fitting function  $V^{\text{fit}}$ .

To study large-scale properties of the differential rotation, it would be prudent to have angular velocities determined independently at different latitudes. A method to derive these quantities has been described recently (Howard and Yoshimura, 1976).

#### Acknowledgements

We would like to thank Dr. Robert Howard for his helpful discussions. This work was supported in part by the Office of Naval Research under Contract N00014-76-C-0207, by the National Aeronautics and Space Administration under Grant NGR 05-020-559, by the Atmospheric Sciences Section of the National Science Foundation under Grants ATM74-19007 and DES75-15664 and by the Max C. Fleischmann Foundation.



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Howard, R. and Yoshimura, H.: 1976, I.A.U. Symposium #71, Basic Mechanisms of Solar Activity, ed. by V. Bumba & J. Kleczek, D. Reidel Publishing Co., Dordrecht, Holland, pp. 19-36.

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### Figure Captions

Figure 1 A scatter plot of the b and c parameters. Each point represents the results of a simultaneous full-disk least squares fit to one day's Mt. Wilson magnetogram doppler shift data (Howard and Harvey, 1970). The differential rotation is assumed to be of the form  $\omega = a + b \sin^2 B + c \sin^4 B$ . The time period of the data is 1966-1969.

Figure 2 A scatter plot of the b and c parameters extracted using simulated data. Full disk doppler shift observations with spatial resolution 17" are simulated by assuming a certain average differential rotation law, calculating the line of sight velocity component at each aperture over the disk due to this differential rotation, and then adding gaussian, random noise to this simulated signal. This simulated data is then analyzed to extract the parameters a,b,c by the same least square method used for the actual observations. This procedure is then repeated, changing the random noise, to obtain the different points in the scatter plot.

Figure 3 Contour plots of the function that is minimized by the least-squares solution. This plot is obtained by varying the parameters b and c in the angular velocity fitting function  $\omega = a + b \sin^2 B + c \sin^4 B$ . The point at the center of the ellipses is a minimum. Logarithmic contour intervals are plotted. The fact that the contours are ellipses and not circles suggests that the noise in the data will not result in an isotropic scattering of points about the center, but in a correlation of b and c along the long axis of the ellipse.

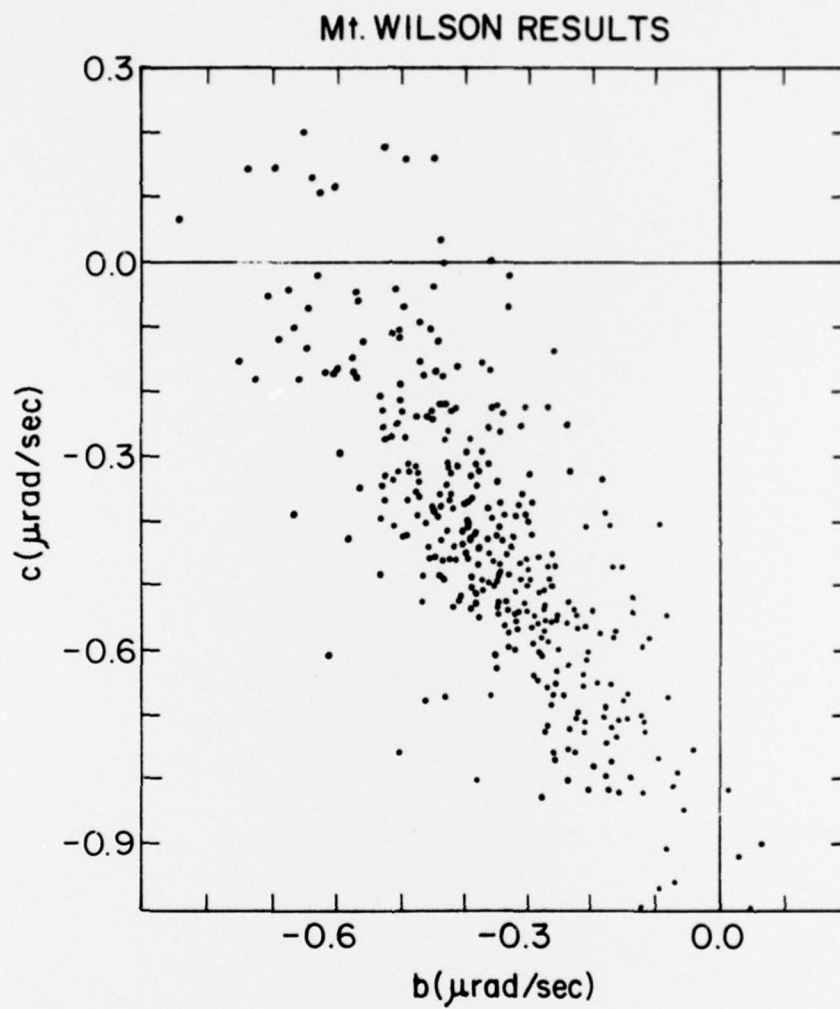


Figure 1

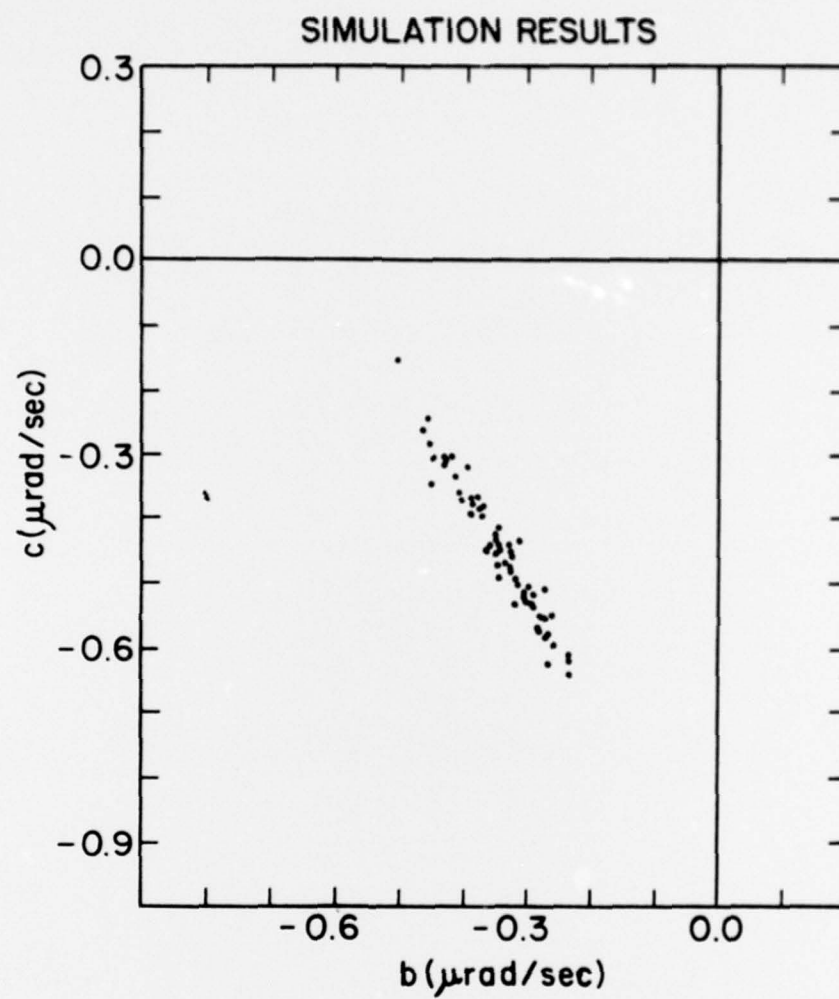


Figure 2



FUNCTION THAT IS MINIMIZED =  $\sum_i [v_i - v^{\text{fit}}(b,c)]^2$

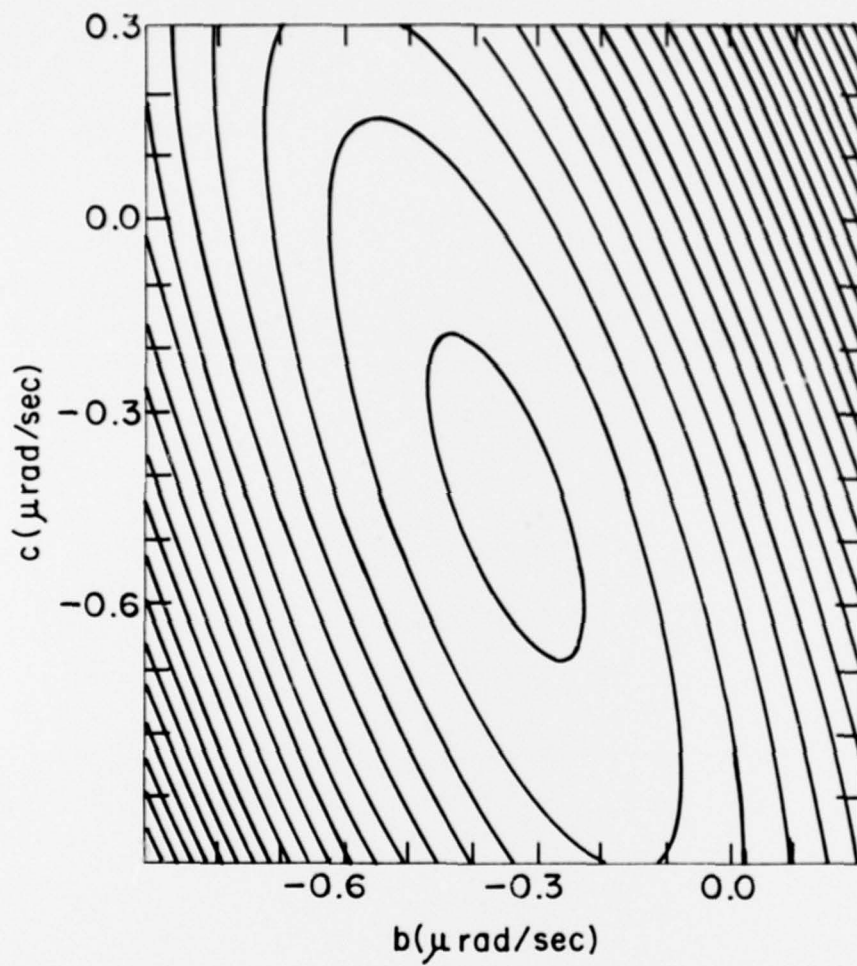


Figure 3